Design and integration of lower ports for ITER diagnostic systems

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HIGHLIGHTS

- Lower port structures are in its conceptual design phase.
- Electromagnetic and seismic loads, will dominate all other mechanical loads.
- Design allows diagnostics support, neutron shielding while and signals transmission.
- Installation and maintenance operations are fully remote handling compatible.

Keywords:
Diagnostic rack
Lower ports
ITER

ABSTRACT

All around the ITER vacuum vessel, forty-four ports will provide access to the vacuum vessel for remote handling operations, diagnostic systems, heating, and vacuum systems: 18 upper ports, 17 equatorial ports, and 9 lower ports. Among the lower ports, three of them will be used for the remote handling installation of the ITER divertor. Once the divertor is in place, these ports will host various diagnostic systems mounted in the so-called diagnostic racks. The diagnostic racks must allow the support and cooling of the diagnostics, extraction of the required diagnostic signals, and providing access and maintainability while minimizing the leakage of radiation toward the back of the port where the humans are allowed to enter. A fully integrated inner rack, carrying the near plasma diagnostic components, will be an stainless steel structure, 4.2 m long, with a maximum weight of 10 t. This structure brings water for cooling and baking at maximum temperature of 240 °C and provides connection with gas, vacuum and electric services. Additional racks (placed away from plasma and not requiring cooling) may be required for the support of some particular diagnostic components. The diagnostics racks and its associated ex vessel structures, which are in its conceptual design phase, are being designed to survive the lifetime of ITER of 20 years. This paper presents the current state of development including interfaces, diagnostic integration, operation and maintenance, shielding requirements, remote handling, loads cases and discussion of the main challenges coming from the severe environment and engineering requirements.

1. Introduction to ITER lower ports

The ITER machine will be a scientific experiment aimed at demonstrating the scientific and technological feasibility of nuclear fusion energy. One of the key aspects of the research program of ITER is the diagnosis of the plasma and the first-wall, e.g. the plasma temperature, density and radiative properties and the first-wall

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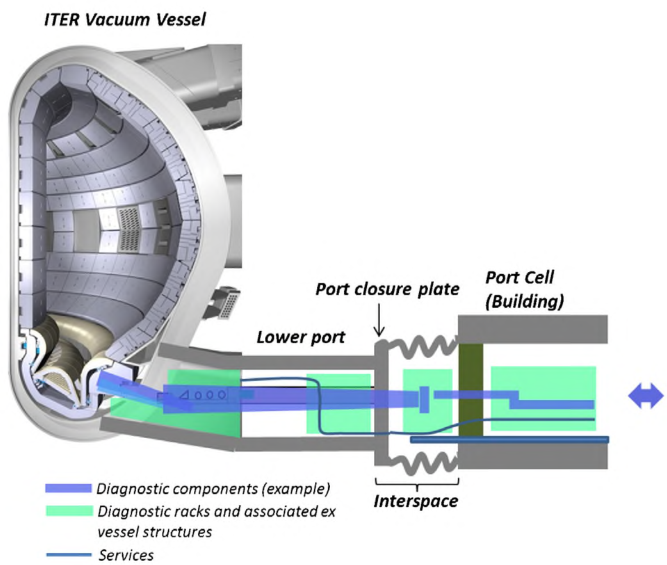

Fig. 1. Lower port location.

temperature, etc. For these purposes, a large number of different types of diagnostic equipment will look into the ITER VV from many different positions: inside the vacuum vessel and in the vacuum vessel ports at the upper, equatorial and lower levels. For the purposes of the present document, we focus on the lower ports, see Fig. 1.

In ITER, there will be 3 ports to be used for the installation, by means of remote handling, of the divertor cassettes. Once the divertor cassettes are in place, these so-called remote handling (RH) ports will be occupied by diagnostics that will look into the plasma from bottom of the machine. Those diagnostics are mounted in the so-called diagnostic racks that are also designed to provide the required neutron shielding and support for diagnostic systems and services.

2. Diagnostic systems in lower ports

In ITER lower ports, some diagnostics will be placed in the divertor cassettes itself. Other important diagnostics will be installed in the diagnostic racks [1]:

Neutron systems, such as *neutron cameras*, to get information for reconstruction of the neutron source profile.

Optical systems: Laser – aided systems, such as *Thomson scattering* which is able to measure the plasma electron temperature and density, *divertor impurity monitor* where spectrometers are designed to supply information on influxes, impurities, ionization, etc., or the *erosion monitor* which is going to provide information on erosion and deposition.

All of these diagnostics will produce signals that will be transmitted, routed and integrated all along the lower port (in- and ex-vessel) toward the analysis station in the diagnostic building where the signals will be processed and analyzed. At the same time, especially those ones placed into the diagnostic rack, will require services such as water cooling, gas supply, connection to vacuum service, electrical supply and connection, optical fibers, etc.

In the next sections, the diagnostic racks and related ex-vessel structures that will support and make possible the integration [2], and installation of the different diagnostic components for a successful transmission of the different signals, will be described.

3. Main requirements and constraints

The main difficulties of implementing diagnostics in ITER come from the environmental conditions, mainly the high levels of neutron flux, contamination by dust and tritium and vacuum conditions too. As a consequence, there are strict engineering requirements that the diagnostics need to meet, especially for in-vessel structures and the diagnostic racks in particular [3].

The Diagnostic racks must comply with the ITER Vacuum Handbook [3], in order to contribute to the achievement of the required ultra-high vacuum conditions. This has implications on permitted leak rates and off-gassing rates, joining techniques, geometry, welding inspection, thermal cycling, testing and quality class. Certain welds of the diagnostic rack pipes (water connections) will be vacuum welds which volume should be 100% inspected.

The radiation level in the cryostat interspace of the diagnostic lower ports following operation, i.e. 1E6 s after shut-down, shall be less than 100 μSv/h. This is set up to allow hands-on maintenance and human access in the port interspace at the lower port closure following machine shut-down. One of the functions of the rack placed inside the port and its services passing through the vacuum boundary is to contribute to achieve this requisite following ALARA (as low as reasonable achievable) principle.

Diagnostic racks are in the way of other internal components requiring maintenance, i.e. divertor cassettes. There will be, then, a strong design driver which is the fully remote handling compatibility expected to be required several times in the ITER life. Once the racks are removed, remote maintenance will be performed in the ITER Hot Cell.

As some functional tests on the diagnostics inside the rack will be needed to be performed, the diagnostic rack is required to be designed compatible with the Port Plug Test Facility [4] where those tests will take place.

The diagnostic rack structures will be designed and manufactured according to the RCC-MR, which is well-known to the French Nuclear Regulators. This will make it consistent with the design of the vacuum vessel, also designed and manufactured to the RCC-MR code.

These racks and related structures are being designed to survive the lifetime of ITER of 20 years being able to withstand all the expected nuclear, electromagnetic and seismic loads among others. The main functions of this diagnostic rack are summarized in Table 1 below:

4. Design of diagnostic racks

4.1. Description

The diagnostic racks are stainless-steel structures with the role of providing diagnostic access at the same time than support, cooling, electrical and gas connection and neutron shielding. This neutron shielding is crucial to protect the vacuum vessel and machine coils from nuclear radiation (neutron, gammas) and hence overheating and to allow hands on operation at the back of the port minimizing the neutron activation of surrounding structures. The Diagnostic Rack is made of stainless steel 316 L(N) – ITER grade material.

The diagnostic rack structure will be divided in the *inner rack* and other *additional racks*.

The *inner rack* is the structure essential for the support of components and nuclear shielding placed near the plasma providing as well connection with diagnostic services as cooling water, gas and cable trays. Those services will be routed inside the port toward the penetrations reserved at the back of the port in the so-called interspace area at both sides of the closure plate. Depending on the

Table 1
Diagnostic rack functions.

Main function	Subfunction
To support diagnostics	To ensure correct attachment of diagnostics To allow positioning of diagnostics
To enable connection with services maintaining the confinement	To allow electrical connection To allow water cooling connection To allow gas connection
To maintain structural integrity	To withstand loads (EM loads, Seismic loads, etc.) during all operational stages: installation, operation, etc. To be supported on vacuum vessel (on dedicated rails for installation of divertor cassettes) To be locked on the rails
To assure maintenance	To allow installation on the tokamak To allow remote maintenance in Hot Cell To be transferred by remote handling
To assure functional tests in Port Plug Test Facility [4]	To allow services connections, functional tests and correct sealing of the port plug test facility tank
To provide neutron shielding	To protect diagnostics To contribute to maintain shut down dose rate below limits at the back of the port closure
To contribute ALARA	To limit exposure of workers
To allow decommissioning	To be constructed and designed to allow the remote handling decommissioning

diagnostic functional requirements, additional supporting structures may be needed as the case of supporting mirrors at the back of the port, near the vacuum closure area, where windows will be placed for optical systems. Then, an *additional rack* will also be placed at the back of the lower port. Fig. 2 shows an scheme of the cross section of the lower port where the inner rack and additional rack are placed.

The diagnostic racks will be supported to the vacuum vessel lower port through the so-called Divertor Rails. At the back of the port, at both sides of a vacuum closure plate, dedicated feedthroughs, which will be permanently attached to the vacuum vessel, are foreseen to serve the diagnostics in the inner rack. From them, the corresponding water piping, gas piping and electrical cabling will run along the port until the connection point at the back of the inner rack, Fig. 3 and Fig. 4. At this point, the electrical connection is done by approaching the different parts of the connector by using remote handling means. Pipes will be welded, also by remote handling, with orbital welding.

The diagnostic inner rack will be manufactured based on a supporting frame that will give the main stiffness to the whole rack.

This frame will also incorporate:

- Guiding wheels that are mounted in the supporting frame, will easy the installation of the rack from the transfer cask to the lower port in such a way that the cantilever handling can be avoided.

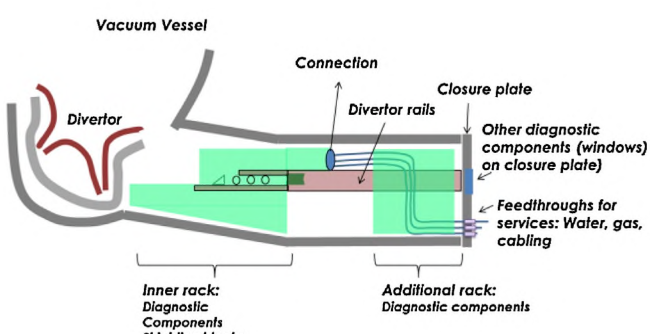

Fig. 2. Lower port section showing inner and additional racks.

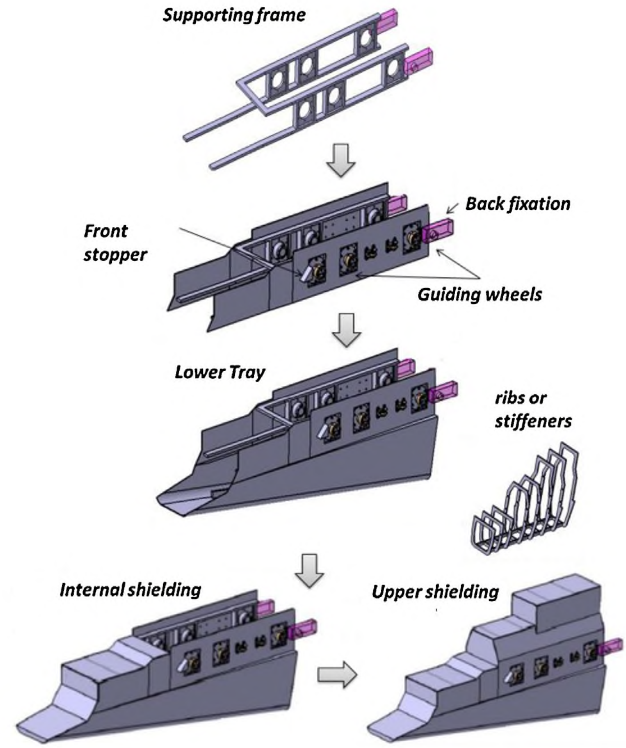

Fig. 3. Different parts of the inner diagnostic rack assembly.

- Front stopper that will fix the rack in the vertical and toroidal directions while, at the same time, is remote handling compatible. This stopper will be developed in Al–Br and without any deployable part in a way that jamming is avoided (especially important in the front part where rescue is challenging).
- Fixation at the back of the rack using dedicated radial rail holes plus adjustment to the C shape of rails (to ensure braking). Final adjustment toward the stoppers can be done also from this point through adjustable bars. It will fix the rack in the three directions.

A lower tray, fixed to the supporting frame, will provide support for different diagnostic components (detector boxes, mirrors and its optical bench). In addition, also internal neutron shielding blocks, required to minimize the neutron streaming through the port, will be attached to it. The material for these shielding blocks is still to be determined port by port where steel, water, tungsten and boron carbide are the main candidates.

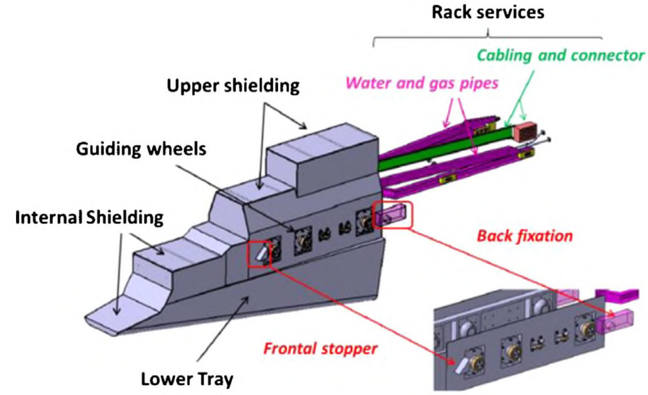

Fig. 4. Diagnostic rack with main components.

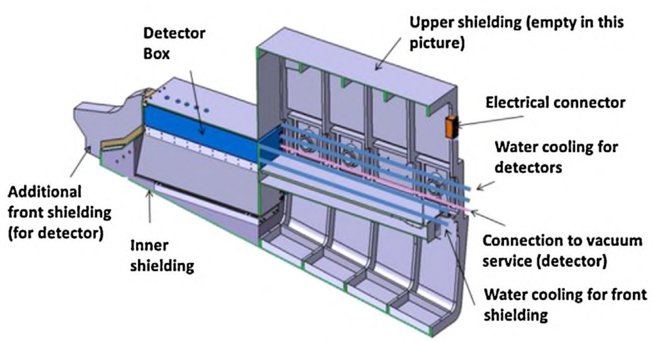

Fig. 5. Example of an integrated diagnostic rack including the Vertical Neutron Camera.

Additional upper shielding blocks will close the upper part of the rack above the supporting frame.

Depending on the integration of the particular diagnostics into the rack, particular regions may need dedicated ribs or stiffeners.

At the back of the rack, three arms will be attached in order to carry pipes, cabling and its electrical connector. It is foreseen to add intermediate supports for these arms to the Divertor Rails to provide the required stiffness during operation.

In the following Fig. 5 an example of an integrated inner rack with Vertical Neutron Camera and some dedicated shielding is shown.

4.2. *Load evaluation*

In this chapter, the main loads acting on the racks are summarized.

4.2.1. *Dead Weight*

The mass of the assembled diagnostic rack will depend on the particular hosted diagnostic system. The mass limit for these structures is 10 tons which is roughly the maximum weight of the divertor cassette. It is expected to reach this limit value in the three ports to incorporate as much as shielding material as possible to minimize the doses in the port interspace. The effects of the accelerated mass during seismic or electromagnetic events will cause the worst scenario for these structures.

4.2.2. *Electromagnetic loads*

Tokamaks structures are occasionally exposed to rapidly changing magnetic fields caused by abrupt (and usually unintentional) termination of the plasma current. These are known as "plasma disruptions" and "vertical displacement events". They occur on the time scale of a few ms up to seconds. The changing magnetic fields induce eddy currents in metallic structures which then interact with the remaining magnetic fields to generate very large forces and torques. It can be of such a magnitude that, together with the seismic events, will dominate all other mechanical load conditions.

Preliminary calculations [5] indicate that vertical displacement events, when the plasma is translated downward will be the worst cases for the diagnostic rack. As an example, a vertical displacement event of category II (or in other words, a likely event expected 300 times) will cause a transient scenario with a maximum radial force of 45 kN, a toroidal force of about 10 kN and a vertical force of about 20 kN. During a vertical displacement event Category III (Unlikely), up to 55 kN will be expected in the radial direction while 12 kN and 25 kN will be produced in toroidal and vertical direction respectively, Fig. 6.

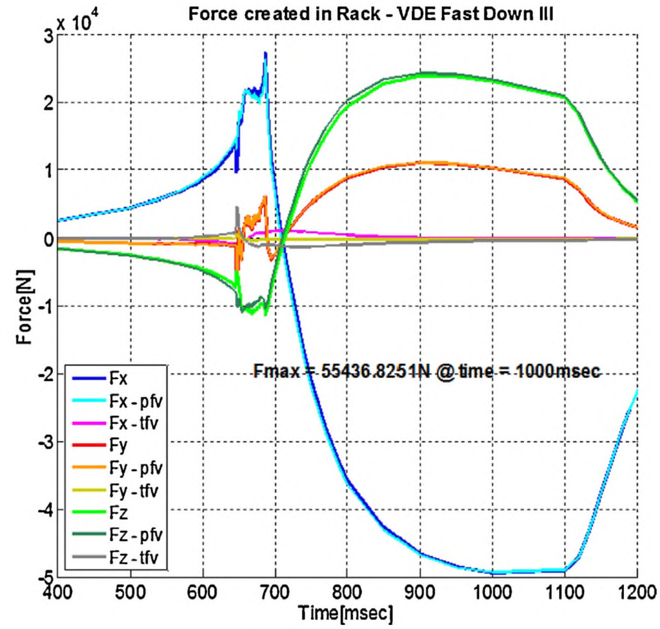

Fig. 6. Electromagnetic forces in rack during VDE III in *x* (radial), *y* (poloidal) and *z* (vertical) during poloidal field variation (pfv) and toroidal field variation (tfv).

4.2.3. *Nuclear heating*

The maximum nuclear heating expected in the rack will be about 0.2 MW/m^3 while the average value in its front area will be about 0.05 MW/m^3 for the inductive scenario with 500 MW of fusion power [6]. In Fig. 7 below, the map of nuclear heating on the rack is show for the mentioned scenario.

During the inductive scenario, pulses of about 450 s will take place with a minimum repetition time of 1800 s. The ramp up of the pulse is estimated to be up to 50 s while the ramp down about 100 s. Under these conditions, and just considering radiation to atmosphere (vacuum vessel very close at 100 °C) with emissivity 0.3 of external surfaces, a maximum temperature of 165 °C was obtained in the front part of the rack. It suggests the possibility of avoid having a fully cooled structure and instead, to directly cool down particular areas, components or shielding placed at the front of the rack. In Fig. 5, where a picture of an integrated rack is shown, the diagnostic rack is not a cooled structure but brings water coolant to the particular components as the front shielding (in this case closer to plasma and then higher values of nuclear heating) and detectors.

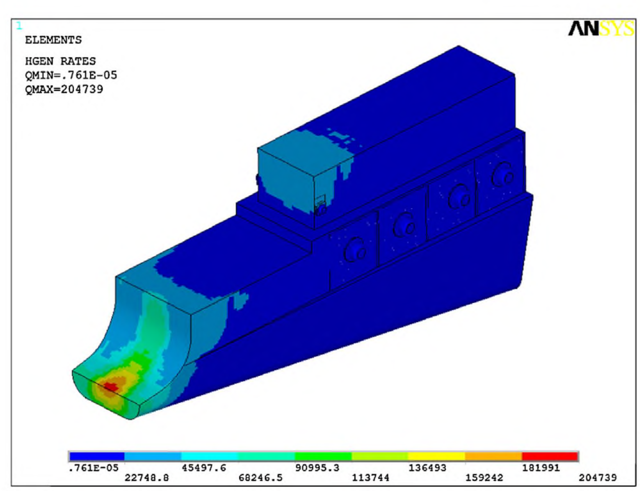

Fig. 7. Map of nuclear heating (W/m^3) in the rack structure.

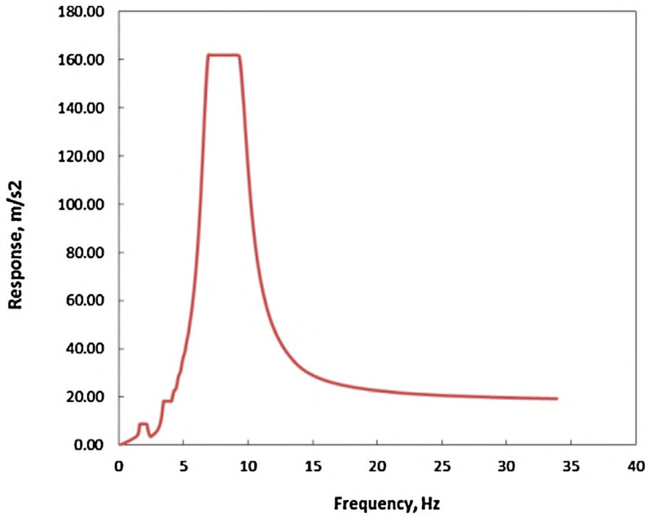

Fig. 8. SL-2 triaxial, damping 4%; broadened FRS at lower port representative point in vertical direction, m/s^2.

4.2.4. *Seismic and other accidental loads*

The strongest seismic event foreseen in ITER is called SL-2, and also known as the Safe Shutdown Earthquake (SSE), defined as a conservative envelop of historical data (SMS) and a paleoseismic analysis of the local region. This event will be an extremely unlikely event but nevertheless, it shall be demonstrated that all safety functions are maintained. Other seismic event that needs consideration is the so called SMHV that will be the most penalizing earthquake liable to occur over a period of about 1000 years, assumed to be equal to SL-2 multiplied by 0.73.

Finally, also a likely seismic event, called SL-1 with a probability in the order of 10–2 per year. Following the Nuclear Pressure Equipment regulation it corresponds to a foreseeable event. It is assumed to be equal to 1/3 of SL-2.

In the following Fig. 8, the Floor Response Spectra of a representative point in the lower port is shown for the vertical direction which is the worst case.

As the diagnostic rack has a high natural frequency, and taking into account a maximum mass of 10 tons, we can estimate seismic loads in the order of 200 kN for SL-2 event.

Other accidental loads include fire events, loss of coolant in the port cells, ingress of coolant into the vacuum vessel or pipe whipping due to integration of neighboring systems. All these events need to be fully analyzed and safety functions guaranteed. It means that the diagnostic rack and its associated structures should guarantee that the vacuum vessel or any other confinement barrier is not damaged during its operation.

4.2.5. *Operating thermal and pressure loads*

Other significant loads are the thermal expansion stresses and pressures associated with normal full power plasma (where water flows at 70 °C and 4 MPa) and baking (where water flows at 240 °C and 4.4 MPa).

In the assessment of the structural integrity of the racks structures, according to the RCC-MR (2007), these loads must be combined and compared against appropriate allowable stresses (Service Levels A, C and D), which vary depending on the probability of the event, e.g. lower probability events have higher allowable stresses. One of the worst combination cases correspond with the seismic event SL-1 that triggers a vertical displacement event category II. The vertical forces expected in this event will raise 90 kN approximately.

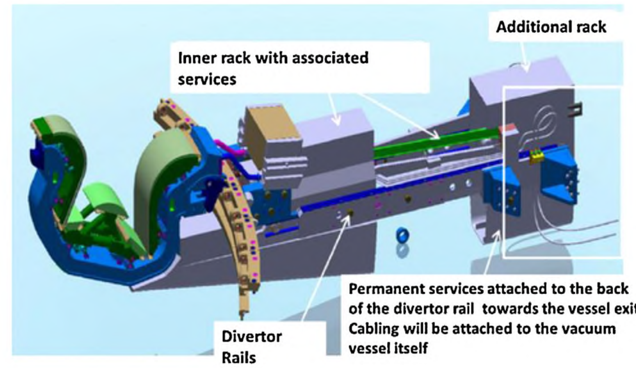

Fig. 9. Diagnostic racks mounted on divertor rack and services connected.

5. Integration of diagnostics in VV and port cells

5.1. *In-vessel integration*

The diagnostic rack, as shown in Fig. 4, will come toward the ITER Vacuum Vessel inside a transfer cask mounted in their internal rails. The transfer cask will dock onto the vacuum vessel port and the closure plate open. Then, by means of the remote handling mover, the rack will be pushed into the divertor rails attached to the vessel (Fig. 2) up to their final position where it is locked. After that, the same remote handling mover, equipped with an articulated arm and tools, will connect the services coming with the rack with their correspondent service permanently attached to the lower port. Fig. 9 represents the entire rack with services attached to the divertor rails.

5.2. *Ex-vessel integration*

Diagnostic components placed ex-vessel will be supported in the so-called Interspace Support Structure (ISS) and Port Cell Support Structures (PCSS) [7].

In the interspace support structure, some equipment as mirrors or fiber bundles that are in line with diagnostic windows placed in the closure plate needs to be accommodated. This structure is represented in Fig. 10 below and it is composed by a chassis that is supported by the building through the remote handling rails supported in cantilever from the bioshield area. This structure is installed from the port cell by remote handling tractor and locked into the rails. Water and gas lines and electrical cabling going to the feedthroughs are located both sides of these structures in such a way that there is no need to remove them to extract the ISS (Fig. 10).

The integration in the port cell is driven by the size of each diagnostic. A configurable frame, Port Cell Support Structures (PCSS), is foreseen to handle the equipment in the port cell. In Fig. 10, the maximum size of PCSS is shown. Some examples of components that this structure will carry are heat exchangers or fiber bundles needed for the diagnostic operation. In the lower port cells, the roof is occupied by many water pipes that will carry activated water. For this reason, it is foreseen that the PCSS will have to also support additional shielding for particular components as optical fibers.

The total maximum load on the port cell rail is created by the fully loaded RH cask with an approximately weigh of 100 t.

5.3. *Summary and future work*

The diagnostics racks and its associated ex-vessel structures are in its conceptual design phase where the key engineering requirements and design constraints have been identified and discussed in this paper.

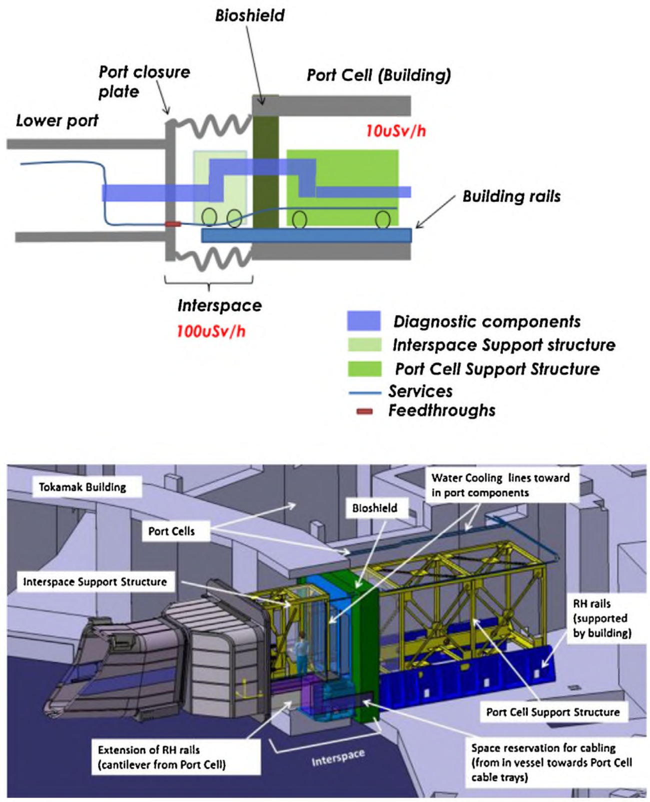

Fig. 10. Lower Port Cell ISS and PCSS with dedicated bioshield.

The presented design allows the support for diagnostic components and neutron shielding while the transmission of the signals and the supply of the required services are guaranteed. Its installation and maintenance operations are fully remote handling compatible.

The electromagnetic loads during vertical displacement events, together with the seismic events, will dominate all other mechanical load conditions. The presented design will withstand these loading conditions in addition with the normal operation (30,000 discharges) throughout the lifetime of ITER for 20 years [8].

The next phases of the design will focus on the detailed electromagnetic, thermal and structural analysis and optimization of the rack geometry and its supporting strategy, optimization of the ISS and PCSS, the refinement of the remote handling, the maintenance process and the reduction of the shut-down dose rates of lower ports following ALARA.

Disclaimer

The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

Acknowledgment

All ITER Organization teams, domestic agencies and associated companies that did possible the work presented in this paper.

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